2014/8

Prospects for Paris 2015: do major emitters want the same climate ?

Simon Buckle, Mirabelle Muûls,
Joerg Leib and Thierry Bréchet

CORE

DISCUSSION PAPER

Center for Operations Research
and Econometrics

Voie du Roman Pays, 34
B-1348 Louvain-la-Neuve
Belgium
http://www.uclouvain.be/core

CORE DISCUSSION PAPER
2014/8

Prospects for Paris 2015: do major emitters want the same climate ?

Simon BUCKLE [1], Mirabelle MUÛLS [2]
Jorge LEIB[3] and Thierry BRECHET[4]

February 2014

Abstract

International negotiations have failed to achieve an ambitious outcome to limit climate risks. A Cournot outcome where countries determine their mitigation commitments in the full knowledge of those by others could be an important step. It would avoid a Stackelberg (leader-follower) outcome where one or more major emitters impose a level of climate risk on the rest of the world. This requires these countries to have sufficiently similar preferences over global cumulative emissions. We develop a novel stylised economic growth model to analyse the dynamics of international negotiations. Economies can be classified according to their committed emissions and the initial level of atmospheric CO_2. We define a new metric, the desired mitigation effort, which provides an empirical methodology for comparing and evaluating countries' mitigation commitments. A numerical calibration suggests a degree of convergence between the major emitters that might allow a Cournot-style agreement at the Paris Conference in 2015.

Keywords: climate change, climate damages, economic growth, game theory, international climate negotiations, mitigation.

[1] Grantham Institute for Climate Change, Imperial College London, U.K. E-mail: simon.buckle@imperial.ac.uk
[2] Grantham Institute for Climate Change and Imperial College Business School, Imperial College London, U.K.
[3] Grantham Institute for Climate Change, Imperial College London, U.K.
[4] Université catholique de Louvain, CORE; Louvain School of Management and Chair Lhoist Berghmans, B-1348 Louvain-la-Neuve, Belgium. E-mail: Thierry.brechet@uclouvain.be

Financial and other support from the Grantham Institute for Climate Change at Imperial College London and from the U.K. Department of Energy and Climate Change under the AVOID programme are gratefully acknowledged. The work has benefited from discussions over a number of years with colleagues at Imperial and LSE and from comments from colleagues at both the WCERE conference in Montréal and the EGU Conference in 2010. Simon Buckle would also like to thank Claude Henry for extremely helpful and encouraging discussions during the early stages of developing this model. All remaining errors are of course the responsibility of the authors.

1 Introduction

To limit climate risks, a substantial and sustained reduction in global energy-related carbon dioxide (CO_2) emissions remains the critical policy and practical challenge. This paper aims to provide qualitative and quantitative insight into some key influences on the dynamics of international climate discussions arising from heterogeneity in national economic and technological endowments.

The main contributions of this paper are threefold. First, we wish to contrast the usual modelling of damages as a reduction in the productivity of an economy with an approach where damages may also destroy capital (and human life)[6]. Recent impacts of extreme weather events, both in developing and rich countries can only reinforce the need for such an approach. Second, we compare the level of mitigation effort by economies at very different stages of economic and technological development, which is a key issue for climate negotiations. Third, we perform some numerical calibrations to understand whether the Cournot equilibrium in mitigation action might be feasible given the diversity of countries that are central to international climate negotiations. We see this latter as an essential stepping stone to potentially more ambitious action.

Central to this analysis is the derivation of what we call the "Desired Mitigation Effort" (*DME*) for each country, closely related to the concept of a "Desired Carbon Budget" (*DCB*) which emerges from the model in a linear utility setting. As is well known (e.g. Wigley et al. 1996 and more recently, Allen et al., 2009), it is the cumulative level of CO_2 in the atmosphere, not the level of annual emissions, which largely determines the change in global mean surface temperature, the most convenient index of climate change. Hence, effective international mitigation requires countries to commit to an emissions path and an allocation of emissions across countries that, either implicitly or explicitly, is consistent with global cumulative carbon emissions corresponding to achieving a given temperature with an agreed probability as given by climate models.

We develop a stylised integrated assessment model to address the above three points. It also enables a symmetrical treatment of the short and long-term, therefore isolating - and facilitating a more effective analysis of – the implications of different weightings over the level and profile of lifetime consumption and the longer-term impacts of climate change[7].

[6] We do not, however, include natural capital or ecosystem services.
[7] This resembles Chichilinsky (1995)'s sustainable preferences approach, but differs in that the model does not focus on the strictly infinite time properties of the utility function, but rather on the impact of climate change on the utility of the bequest from current to future generations.

This is particularly useful in view of the controversy over discount rates, which has clouded climate policy discussions (Stern, 2013). Additionally, in the limit of linear utility, the model delivers analytical results and is simple enough to allow extension to study technological change and adaptation (see Leib, 2013). Fully articulated and well-developed integrated assessment models would not allow such an analysis. Whilst they can provide analysis of Cournot behaviour for particular regions, they model damages as impacting on productivity (Nordhaus, 2010), and/or highlight the collective action problems of securing an effective international agreement (e.g. Bosetti et al. 2009, Bréchet et al. 2011). A benchmark model is first considered where the world behaves as a representative agent that maximises global social welfare. We then extend to a two-country model. Social welfare is a function of both the short-term (i.e. consumption in periods one and two) and the impact of climate damages on a bequest made to future generations.

How do our results relate to current international negotiations on climate change? Whatever the eventual level of cumulative CO_2 emissions, one way to look at the current phase of the negotiation process is as a form of discovery. For a number of reasons, countries are unsure of both the long-term marginal and absolute costs of ambitious mitigation and of its benefits in terms of avoided climate and other damages. National mitigation commitments are framed in terms of reductions in the flow of emissions or in emissions intensity by a certain point of time relative to a baseline. Despite a professed commitment to a 2ºC international target, current action falls short of that needed to achieve a 2ºC increase in global mean temperature target (UNEP, 2013). National targets are therefore at best an imperfect signal of countries' - perhaps yet to be determined - preferences over the global level of cumulative emissions, coloured as they are by political, economic and social perspectives in addition to – and sometimes overshadowing – our scientific understanding of climate change.

Game theory considerations can provide a simplified view of the intuition we have in mind. The illustrative framework in Figure 1 shows a theoretical two-country world in which representative agents have choices over the ultimate level of their cumulative emissions. The negotiations so far have aimed at moving beyond Business as Usual levels of cumulative emissions towards the most environmentally effective "cooperative" outcome within a relatively short period of time, despite less than propitious economic and technological circumstances. There is a large literature on the difficulties of reaching a fully co-operative outcome to international climate policy (see Bréchet et al. 2011 and Barrett, 2003 for a discussion). Global-level negotiations on their own may also be inadequate in building the levels of trust and transparency needed for an effective climate change regime (see Ostrom, 2009)[8].

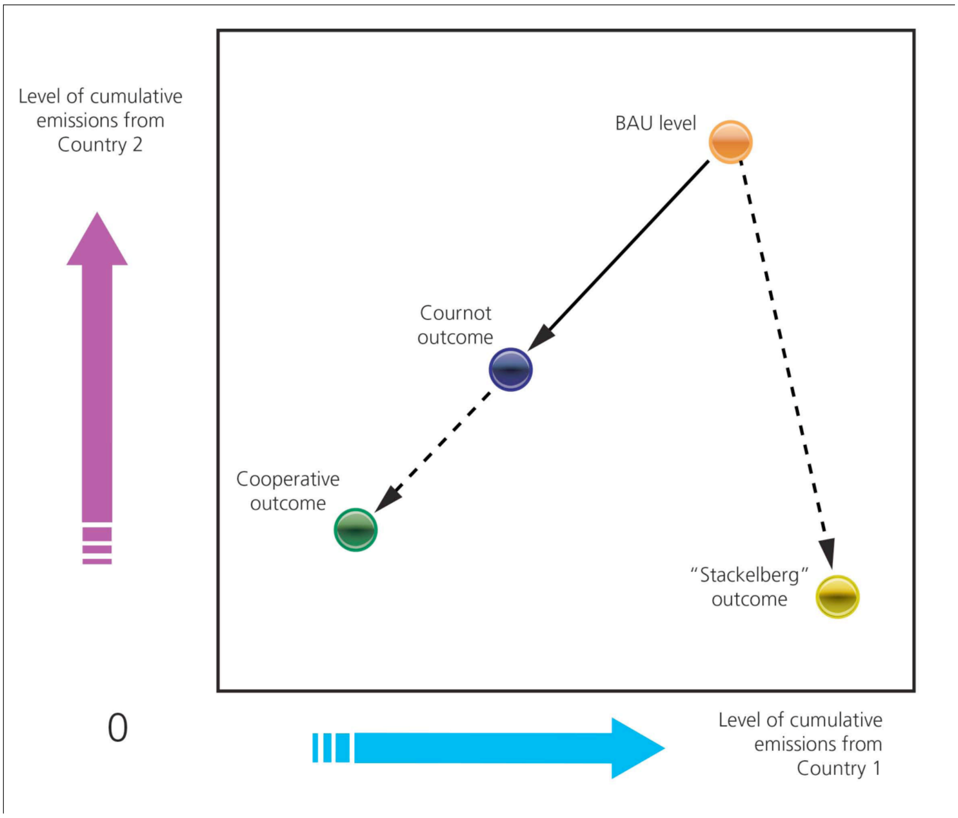

Figure 1. An illustrative emissions reduction game for two countries**.**
(Countries start at the BAU level and can gradually move to either the non-cooperative Cournot or the Stackelberg outcome. In the case of the Cournot outcome, negotiations might subsequently improve on this by moving the countries closer to the co-operative level of cumulative emissions.)

However, given heterogeneity in economic scale, investment and levels of emissions, and the presence of a limited number of major emitters there is a real risk that the world could end up in a "Stackelberg" or leader-follower outcome instead (the yellow circle in Figure 1), where one or more large emitting countries exercise first mover advantage and reduce the carbon budget available for others. The decisions of a few major emitters would then determine the climate risks and outcomes faced by the rest of the world.

Theory suggests that the result of a negotiation process on the quantity of cumulative CO_2 emissions could instead be a Cournot equilibrium, where each country determines its own level of mitigation effort taking that of the other country as given. Although the level of

[8] Edenhofer et al. (2012) review the incentives for unilateral action (such as co-benefits and technological leadership) and decentralized efforts that might alleviate these collective action problems.

mitigation would almost certainly be insufficient to achieve the sort of ambitious goals currently under discussion, securing such an outcome in the short-term could have two important benefits. First, it would provide the basis for a more ambitious co-operative agreement at a later stage with more advanced technologies, greater levels of trust between parties and effective monitoring and verification systems in place. Second, a credible and sufficiently ambitious Cournot outcome would be the most effective way of ensuring we avoid something worse, i.e. the Stackelberg outcome or an inability to move from BAU levels. Reaching agreement on such an outcome may therefore be the critical challenge for the 2015 Paris meeting of the UNFCCC Conference of the Parties (COP 21).

The rest of this paper is structured as follows. In Section 2, we present a world economy model with a single representative agent. Section 3 describes the key results and discusses their implications for climate policy. In Section 4, we extend this approach to a two-country world where climate change becomes an externality. Section 5 provides a calibration of the world economy model and a calibration of individual countries' desired mitigation effort. Section 6 offers concluding remarks on the relevance of this work to the international climate negotiations.

2 A world economy model

Time is discrete and is divided in three periods. Production and its related emissions only take place in the first two periods. We consider a simple carbon cycle in which a constant fraction of the stock of CO_2 above some reference level (S_n) is absorbed by other components of the earth system in each period. If we denote by S_0 the initial CO_2 stock, cumulative CO_2 levels at the end of the two periods of production/consumption are given by:

$$S_t = \delta(S_{t-1} - S_n) + \gamma K_t + S_n \qquad \forall\, t = 1, 2 \qquad (1)$$

Here γ is the emissions coefficients per unit of capital K deployed in each period and (1-δ) is the fraction of CO_2 which is naturally absorbed when CO_2 levels are above their neutral pre-industrial value, S_n. The change in temperature above its neutral level is a logarithmic function of the level of atmospheric CO_2 and the climate sensitivity, Λ (see Myhre et al. (1998) for details). For a range of levels of CO_2 above its neutral level[9], we can approximate the change in temperature in a given period in relation to the level of CO_2 in the previous period by the following relationship:

$$\Delta T_t = 5.35\Lambda ln\frac{S_{t-1}}{S_n} \sim 5.35\Lambda\frac{S_{t-1} - S_n}{S_n} \qquad (2)$$

[9] See Appendix 2 for more details.

As it is common in the literature, climate damages in period t (D_t) are assumed quadratic in the contemporaneous temperature change[10]:

$$D_t = b_t(\Delta T_t)^2 \tag{3}$$

where b_t>0 is a scale parameter that may depend on time. Using the two last equations, the damage function is:

$$D_t = B_t(S_{t-1} - S_n)^2 \qquad \forall\, t = 1, 2, 3 \tag{4}$$

where $t=3$ refers to long term damages and

$$B_t = b_t\left(\frac{5.35\Lambda}{S_n}\right)^2 \tag{5}$$

Damages can thus be expressed as the difference between the cumulative level of CO_2 at each period and their pre-industrial level. Because concentrations are driven by capital accumulation, there also exists a relationship between economic activity and the cumulative emissions. We adopt a deterministic approach since the risk of catastrophic events seems to be a secondary influence on the dynamics of international climate negotiations (see Barrett and Dannenberg, 2012).

We can now explicitly introduce the important idea that damages are to some extent dependant of the stage of development of the economy, represented here by the level of physical capital. First, damages can be due simply to loss of consumption (broadly interpreted) that is independent of physical capital – for example, loss in tourism revenue due to changed weather patterns. Second, with damages dependent on capital, we capture the extent to which having more physical assets exposed to climate damages may increase the scale of climate damages, for example flood damage in a city. Such a representation cannot be introduced in a damage functions in which the temperature increase is the argument. This means that the scale parameter B will depend on K:

$$B_t = B(1 + \epsilon K_{t-1}) \qquad \forall t = 1, 2, 3 \tag{6}$$

where ϵ>0 captures the sensitivity of damages to the level of capital. Parameter B_t is defined as the economic sensitivity to climate change. Consumption is assumed to take place within periods 1 and 2 and is given by the GDP net of both investment and climate damages - in effect, "green consumption":

[10] Impacts of climate change in aggregate are assumed non-negative for the cumulative emissions ranges under consideration. The model can be easily adapted to include any benefits that may occur for short term/small temperature increases.

$$C_t = A_{t-1}K_{t-1} - (K_t - (1-d)K_{t-1}) - B_t(S_{t-1} - S_n)^2 \qquad \forall t = 1, 2 \tag{7}$$

Here A_t is the total factor productivity, d the capital depreciation rate, and B_t the economic sensitivity to climate damages. In the last period there is a bequest to future generations that is simply K_2 net of long term climate damages:

$$\mathcal{B}_3 = K_2 - B_3(S_2 - S_n)^2 \tag{8}$$

We assume that the utility of the representative agent is separable in consumption and the bequest, so that the representative agent's utility function over time is given by:

$$U[C(1), C(2);\ \mathcal{B}(3)] \equiv \omega U[C(1), C(2)] + (1-\omega)U[\mathcal{B}(3)] \tag{9}$$

where ω represents the weight on present discounted utility $(0 < \omega < 1)$. We also assume that the utility is separable in time for consumption in different periods, i.e.:

$$U[C_1, C_2] = U[C_1] + \beta U[C_2] \tag{10}$$

Here $\beta \equiv \frac{1}{1+\theta}$ and θ is the pure rate of time preference. Finally we assume that utility exhibits a Constant Relative Risk Aversion (CRRA) form, i.e.:

$$U\big(X(t)\big) = \frac{X(t)^{1-\eta} - 1}{(1-\eta)} \tag{11}$$

The marginal utility with respect to X (which may represent either consumption or the bequest) is then given by $U'(X_t) = X^{-\eta}$. The parameter $\eta \geq 0$ is the Arrow-Pratt coefficient of relative risk aversion and its inverse is the inter-temporal elasticity of substitution of consumption between two points of time:

$$\eta = -\frac{CU''}{U'} \tag{12}$$

So the smaller η, the more willing the agent is to trade consumption in one period for consumption in another in response to small changes in interest rates.

3 Preliminary results for the world economy model

We first analyse the properties of this benchmark model where the world behaves as a single representative agent. We will successively consider the "Business as Usual" (BAU) scenario (myopic agent, no policy), then a far-sighted agent solution, and finally the analytically soluble case with a linear utility function.

3.1 Myopic behaviour (Business as Usual)

The representative agent maximises discounted utility from consumption in the standard way but is myopic and does not value the long-term bequest. In this "Business as Usual" (BAU) case, ω in Equation (9) is set equal to one and the welfare function is simply:

$$W_{BAU} = U[C(1)] + \beta U[C(2)] \tag{13}$$

To solve, we set the level of $K_2=0$ since production beyond period 2 has no value. The first order condition for K_1 yields the following optimal condition:

$$\frac{\beta U_2'}{U_1'} = \frac{1}{[\{(1-d)+A_1\} - \{\epsilon B(S_1 - S_n)^2\}]} \equiv \frac{1}{H} \tag{14}$$

The marginal rate of substitution of period-one consumption for discounted period-two consumption is equal to the inter-temporal price of period-two consumption in units of period-one consumption. When this price is low (i.e. H is large), investment in period one yields high returns and the discounted marginal utility in period two will be small relative to marginal utility in period one. When $\varepsilon=0$, we have the textbook result for inter-temporal consumption smoothing, but when damages depend on the level of capital (i.e. $\varepsilon>0$), the price will increase with climate damages in period two, making it less attractive to invest and reducing the final level of CO_2.

Climate damages here depend not only on ε and B but also on the initial capital (K_0) and CO_2 endowments. The higher these are, the lower is the incentive to invest for the future. Consumption is falling over time whenever $U_2' > U_1'$ i.e. when marginal climate damages are large relative to capital productivity net of depreciation:

$$0 < \beta[\{(1-d)+A_1\} - \{\epsilon B(S_1 - S_n)^2\}] < 1 \tag{15}$$

Rising consumption is only optimal when marginal climate damages are small relative to the direct returns to investment:

$$\beta[\{(1-d)+A_1\} - \{\epsilon B(S_1 - S_n)^2\}] > 1 \tag{16}$$

This provides some intuition about national strategies when heterogeneous countries co-exist (see below).

3.2 Far-sighted behaviour

Arguably, a socially optimal climate policy should be concerned about the impact of climate damages on productive possibilities for future generations. There exist at least two ways to model this. First, we could include in the social welfare function the *level* of the bequest net of climate damages and we would set $\omega>0$ in Equation (9). Alternatively, the agent might be concerned with the *disutility* of climate damages on the bequest, which is the level of the bequest net of climate damages relative to its counterfactual value without damages. Clearly, for CRRA utility with $\eta>0$, the disutility of damages would be largest for smaller levels of bequest. Here we choose the second version and the social planner maximises the following social welfare function:

$$W_{FAR} \equiv U[C_1] + \beta U[C_2] + \Phi \left[U[\mathcal{B}_3] - U[\overline{\mathcal{B}_3}]\right] \tag{17}$$

The bequest in the absence of long-term climate damages is defined simply as the level of capital bequeathed, which we express as a fraction (1-α) of the net resources available in period two after taking account of climate damages:

$$\overline{\mathcal{B}(3)} \equiv K_2 = (1-\alpha)\{A_1K_1 + (1-d)K_1 - B(2)(S_1 - S_n)^2\} \tag{18}$$

The affine properties of the utility function allow the weight on the long-term to be defined as:

$$\Phi \equiv \frac{(1-\omega)}{\omega} \tag{19}$$

We leave open the possibility that $\Phi = f(\gamma, K_0)$.

We use the same functional form for climate damages as in Equation (3). The detailed solutions to this problem are given in Annex 1. By combining the first order conditions for K_1 and α, we find the inter-temporal condition for marginal utilities:

$$\frac{\beta U_2'}{U_1'}\left\{1 - \frac{2\gamma\Phi B}{\mathrm{H}}(1+\epsilon K_2)(S_2 - S_n)\frac{U_3'}{\beta U_2'}\right\} = \frac{1}{H} \tag{20}$$

where H is defined as in Equation (14).

Comparing with the myopic case (see Equation (14)), we immediately note that if the parameter Φ is set to zero, this reduces to the BAU solution, as it should. For $\Phi>0$, the term within the curly bracket will always be less than unity if $S_2>S_n$ and for non-zero, positive values of the other parameters. In other words, optimally there will always be more mitigation than in the BAU case for a given positive value of H since, in the absence of an alternative clean technology, the agent chooses optimally to shift consumption into period one relative to the BAU case, reducing marginal long-term damages.

We can define the Desired Mitigation Effort (*DME*) as the key (composite) parameter determining the scale of mitigation relative to the BAU case:

$$DME \equiv \Gamma = \frac{2\gamma\Phi B}{\mathrm{H}} \tag{21}$$

DME increases with the size of Φ and is inversely related to H, the *inter-temporal price*, which also has slightly offsetting indirect impacts on behaviour through K_2. *Technology* has an unambiguous effect on both *DME* and H (through S_1): the dirtier the technology, the greater will be the extent of optimal CO_2 mitigation. The same is true for the *sensitivity to climate damages,* ϵ, and the size of the *climate damage parameter*, B.

3.3 Desired Carbon Budgets

Understanding the detailed behaviour of Equation (20) in general requires numerical calibrations, which we provide in Section 5. It is however useful to examine the limiting, (though admittedly unrealistic) case of a linear utility function (η=0), which admits analytical solution. This corresponds to the representative agent being infinitely willing to shift consumption in response to small changes in H. As we shall see, this case helps us to understand the mitigation incentives of different economies and therefore provides some insight into the dynamics of the international climate change negotiations.

The social welfare function now becomes:

$$W_{FAR} \equiv C_1 + \beta C_2 - \Phi B(S_2 - S_n)^2 \tag{22}$$

Note that this depends only on the lifetime present value of consumption and long-term climate damages, with $K_2=0$ optimally. This yields a solution for the optimal level of net cumulative emissions (Ω^*) – in effect the *Desired Carbon Budget (DCB)*, of which some has already been used since $S_0>S_n$ by construction:

$$\Omega^* \equiv DCB \equiv (S_2^* - S_n) = \frac{\beta H - 1}{2\gamma\Phi B} \tag{23}$$

The *DCB* is determined by equating the net marginal benefit of investing and emitting an extra unit of CO_2, which is $\frac{\beta H-1}{\gamma}$, and the long-term marginal climate damages from emitting an additional unit of CO_2, which is $2\Phi B(S_2\text{-}S_n)$. Note that the marginal benefit of emitting an additional unit of CO_2 increases as the emissions intensity falls and, in this linear case, we see a strong rebound effect which is strongly moderated by consumption smoothing when $\eta>0$. We would also see a smaller rebound effect even in the linear utility model if Φ

depended inversely on γ, which would imply that countries with cleaner technology cared more about the long-term[11].

Together with non-negative C_1 and C_2, the linear utility model provides a simple two-dimensional classification scheme for different possible economic worlds based on the level of initial endowments of: (*i*) atmospheric CO_2; and (*ii*) first period or "committed" emissions, γK_0, both scaled by Ω. The position of a theoretical possible world in this two-dimensional parameter space completely determines its behaviour.

Figure 2 illustrates six cases when for simplicity, damages are not sensitive to capital and there is no capital depreciation. In Region 1, it would be able to optimize freely. While a world with large committed, γK_0, would find it optimal to disinvest (mitigate) strongly (Region 1a – perhaps typified by rich, developed economies), a world with lower committed emissions would mitigate less strongly and continue to invest, though at a lower level than for the BAU case (Region 1b – perhaps exemplified by China and India, now taking on voluntary emissions intensity reductions). With η=0, the agent would choose the same *DCB* anywhere within in Region 1. This strong conclusion is of course modified for η>0.

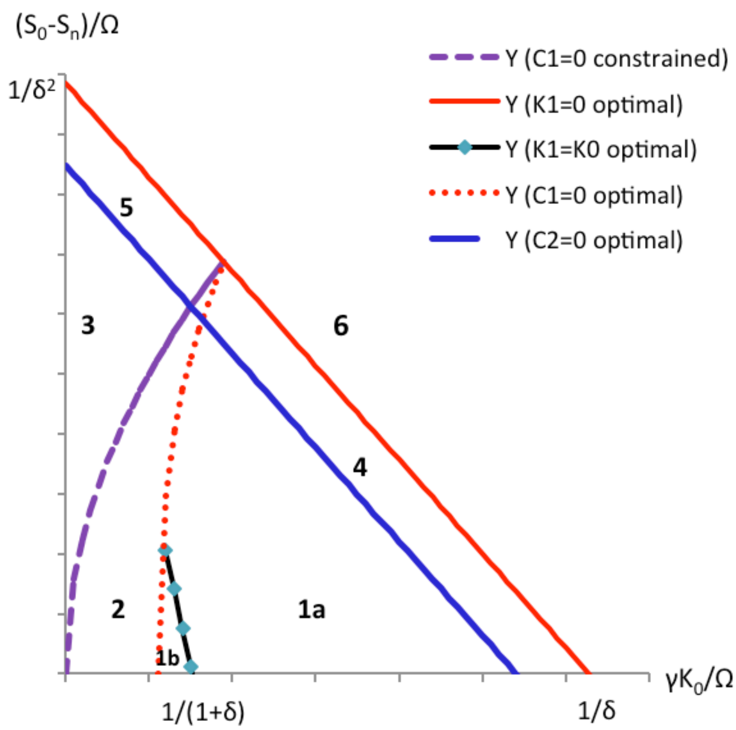

Figure 2. Economic classification scheme for illustrative parameter values.

[11] See Keulartz et al. (2004) for a discussion of the ethical challenges stemming from technological change and development in different contexts.

Region 2 represents an economy where committed emissions are even smaller relative to Ω, because the capital endowment is smaller and/or the technology is cleaner. The marginal benefits of investment exceed the long-term marginal damages and there is no optimal solution as in Equation (23). A world in Region 2 would behave myopically and investment would be resource constrained.

For a world in any of the four remaining regions (3, 4, 5 and 6), climate damages would exceed the resources available for consumption in one or both periods. If initial CO_2 and sensitivity to climate damages are sufficiently high relative to the capital endowment, then the world cannot achieve positive consumption in period one (Region 3 – perhaps typified by a vulnerable small island state). If committed emissions and the initial level of CO_2 are sufficiently high then the world will be unable to achieve positive consumption in period two[12]. This corresponds to Regions 4 and 5 (in the latter, positive consumption is also unattainable in period one).

The outer limit of economic feasibility is set by the solid line representing the point at which the level of capital in period two is zero. This boundary is set by the carbon cycle, with the upper limit for the y-axis scaling as ($1/\delta^2$), and for the x-axis as ($1/\delta$). If, as expected by the IPCC (2013), more emitted CO_2 remains in the atmosphere as climate change progresses, the domain of economic feasibility will shrink.

3.4 The relationship between DME and DCB

The *DME* is a property of a possible world within this model whatever the initial capital, technology and CO_2 endowments and precise form of the utility function. The *DCB* on the other hand exists only in the limiting case of linear utility and even then, only when these endowments position a possible world within Region 1 of Figure 2. In such cases, it is straightforward to see that *DME* is inversely related to the *DCB*:

$$\Gamma = \left(\beta - \frac{1}{H}\right)\frac{1}{\Omega^*} \tag{24}$$

The multiplication factor here is just the difference between the discount factor, β, and the inter-temporal consumption price in the myopic case (Equation (14)), which in Region 1 is positive.

So far we have confined ourselves to a one country setting. However, countries are heterogeneous and the *DME* or *DCB* for one country might be quite different to that for another different country. This matters enormously when, as they do now, a small number of

[12] This is due to the assumption that production in period one uses the entire capital endowment, which we could relax.

countries are responsible for the majority of global CO_2 emissions. To understand how the realised level of cumulative emissions globally might relate to the optimal preferences of multiple individual countries, we now turn to a two-country version of the model.

4 Two-country model

We use a two-country version of our model to show how the intuitions in the world economy case relate to the more realistic and complex situation when there are several countries that act strategically. Each country (labelled by i, j) has a single technology with different productivity and emissions characteristics to capture real-world diversity. Initial endowments are also allowed to vary. Global cumulative CO_2 levels at the end of period t are the sum of the individual country emissions and are given by:

$$S_t = \delta S_{t-1} + \left(\gamma_i K_{i,t-1} + \gamma_j K_{j,t-1}\right) \qquad \forall t = 1, 2 \tag{25}$$

The coefficient of emissions intensity, γ, may differ across countries, but is assumed constant through time. The initial level of CO_2 is again S_0 while we have set $S_n=0$ to save on notation. Damages suffered by the i[th] country in period t can be written in the same way as for the one-country model, except that emissions from both countries now contribute:

$$D_{i,t} = B_{i,t}\, S_{t-1}^2 \qquad \forall\, t = 1, 2, 3 \tag{26}$$

Green consumption within each period t for the i[th] country is given by:

$$C_{i,t} = A_{i,t-1} K_{i,t-1} - \left(K_{i,t} - (1-d) K_{i,t-1}\right) - B_{i,t} S_{t-1}^2 \qquad \forall t = 1, 2 \tag{27}$$

We have assumed a common depreciation rate across countries. As before, consumption must be non-negative. The bequest to future generations is again $K_{i,2}$ net of long term climate damages:

$$\mathcal{B}_{i,3} = K_{i,2} - B_{i,3} S_2^2 \tag{28}$$

We also define a bequest in the absence of long term damages, which is simply equal to the capital passed on to the next generation in each country:

$$\overline{\mathcal{B}_{i,3}} \equiv K_{i,2} = (1-\alpha_i)\left\{A_{i,1} K_{i,1} + (1-d) K_{i,1} - B_{i,2} S_1^2\right\} \tag{29}$$

Using similar notation to the one-country case, each country has a representative agent who maximises a welfare function for that country:

$$W_i \equiv U_i\left[C_{i,1}\right] + \beta_i U_i\left[C_{i,2}\right] + \Phi_\mathrm{i}\left[U_i\left[\mathcal{B}_{i,3}\right] - U_i\left[\overline{\mathcal{B}_{i,3}}\right]\right] \tag{30}$$

We now assume a linear utility function to make easy comparison with Section 3.3. The representative agent for country *i* balances short-term consumption in the first two periods against the level of long-term climate damages to determine the optimal level of capital $K_{i,2}=0$:

$$W_{i,\,linear} = C_{i,1} + \beta_i C_{i,2} - \Phi_i B_i S_2^2 \tag{31}$$

The long-term damages take this simple form because each agent optimally uses up its resources in the first two periods and therefore $K_{i(j),2}=0$.

We recall from the Introduction that one of the possible outcomes in this situation is a Cournot equilibrium. Assuming that constraints on consumption are satisfied and that the behaviour of country *i* does not strategically influence that of country *j*, we can solve the first order conditions for $K_{i(j),1}$ to find the *DCB* for country *i*:

$$\Omega_i^* = \frac{\beta_i\left[\left(1 - d + A_{i,1}\right) - \epsilon \mathrm{B_i} S_1^2\right] - 1}{2\gamma_i \Phi_\mathrm{i} \mathrm{B_i}} \tag{32}$$

The same equation holds for country *j* with just an interchange of labels. So the equation for the *DCB* for each country takes exactly the same form as the optimal global *DCB* in the one-country model. The difference here is that climate change has now become an externality since both countries are contributing to cumulative emissions and damages.

The actual or realised cumulative level of atmospheric CO_2 must of course be a unique value given by the sum of the emissions from both countries:

$$S_2^{act} = \delta^2 S_0 + \delta\left(\gamma_i K_{i,0} + \gamma_j K_{j,0}\right) + \left(\gamma_i K_{i,1} + \gamma_j K_{j,1}\right) \tag{33}$$

An obvious but important point is that a symmetric Cournot equilibrium will only exist if and only if the *DCB* is equal across both countries:

$$\Omega_i^* = \Omega_j^* \tag{34}$$

However even this serendipitous case admits an infinity of solutions depending on the division of the cumulative emissions between countries. Thus, while the cumulative level of CO_2 is fully specified, the allocation of emissions between the two countries is not determined in this model and this will depend on their respective economic capacity and political bargaining power. But at least a Cournot outcome would be feasible.

Our main interest here is in whether the major emitting countries are sufficiently similar in their *DCBs* - or more generally their *DMEs* defined analogously to Equation (24) - for there to be a realistic prospect of agreement on a Cournot-type outcome at the Paris 2015 COP meeting. Or are the *DCBs* so different across major emitters that one or two of them could move the world to a (less appealing for others) Stackelberg equilibrium? The numerical calibrations in the next section allow us to provide some results on these issues.

5 Calibration, numerical results and analysis

We first provide a calibration of the world economy model in order to demonstrate the behaviour of the model in both the BAU and far-sighted versions and analyse how optimal behaviour depends on key parameters such as Φ and η. We then calibrate Equation (21) to provide an initial estimate of *DME* for countries that constitute the Major Economies Forum[13] (MEF) and four of the poorest developing economies (Ethiopia, Bangladesh, Kenya and Chile). Together these countries account for nearly three-quarters of global CO_2 emissions from fossil fuel and cement production.

5.1 The world economy

Parameters used for the calibration are reported in Appendix 3. Figure 3 demonstrates how the weighting on long-term climate damages increases mitigation effort relative to the BAU case (Φ=0) and how this effect is amplified by increases in the utility parameter, η. A strong consumption smoothing motive eventually becomes incompatible with a high weighting on long-term damages for a sufficiently dirty technology.

[13] Launched in 2009, the MEF's purpose was to foster a positive dialogue among major developed and developing economies in the run-up to the UN climate change conference in Copenhagen and beyond. The European Union as a whole is also part of the MEF, but we chose to focus our analysis on those European countries that are part of the MEF in their own right. See http://www.majoreconomiesforum.org/ for more details.

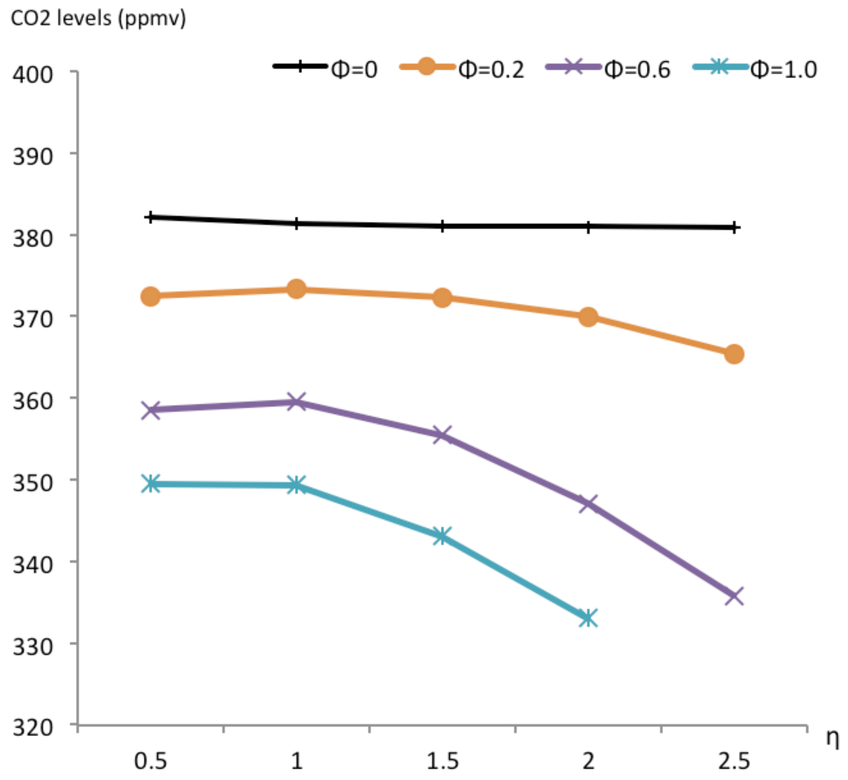

Figure 3. Variation in optimal final atmospheric CO_2 levels (ppmv) with parameters η and Φ.

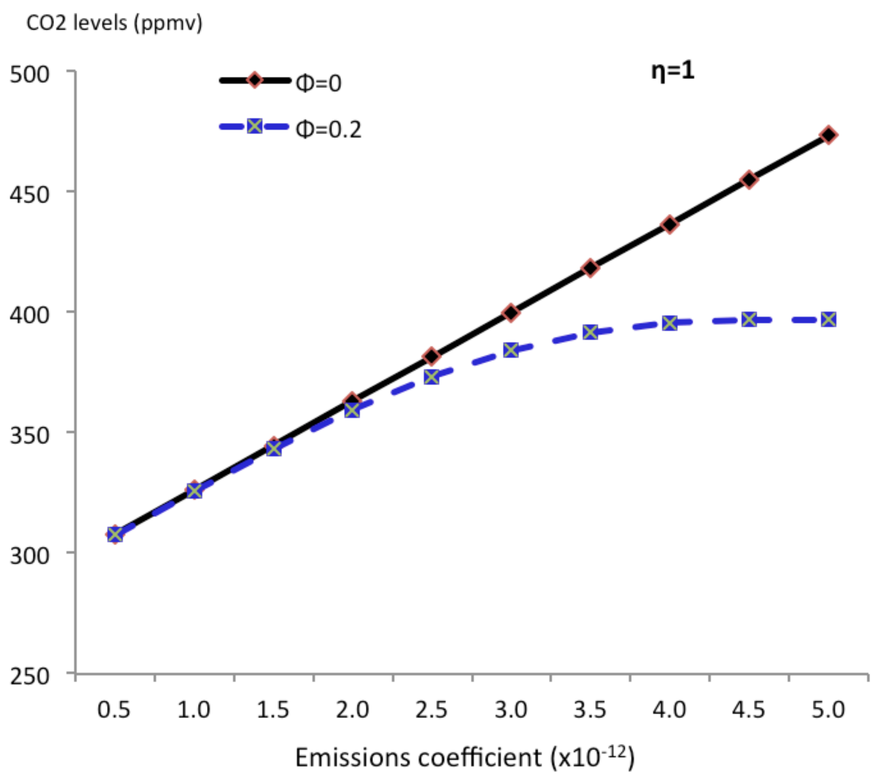

Figure 4. Divergence in final CO_2 levels between the BAU and FAR solutions as the emissions coefficient varies.

Figure 4 shows the dependence of final CO_2 levels in both the BAU and the far-sighted cases on technology for η=1. In BAU, CO_2 concentrations reach 470 ppmv for the dirtiest technology shown, while even Φ=0.2 results in strong mitigation, with final CO_2 levels reaching only 400 ppmv for the same technology. Final CO_2 levels in the far-sighted case are smaller for cleaner technologies; the strong rebound effect from the greater marginal benefit of emitting CO_2 is offset by consumption smoothing.

The sensitivity of damages to the level of capital is an important determinant of the optimal solution and the *DME*, as we shall see in our calibration of individual countries, to which we now turn.

5.2 Desired Mitigation Effort (*DME*) for selected countries

The relevant country parameters are reported in Appendix 3. These are based on economic data from the Penn World Tables Version 6.1 (see Heston et al. (2002)) and CO_2 data from Boden et al. (2010).[14] The series of the physical capital stocks, *K*, is derived applying the perpetual inventory method as in Hall and Jones (1999) or Bonfiglioli (2008).

The initial stock of capital, K_0 is estimated as:

$$\frac{I_0}{(g+d)}$$

where *I* is investment at time 0 and *g* is the average geometric growth rate of total investment between *t* and *t+10* years. Given that according to this method, depreciation is already taken into account for the construction of a measure of capital, the depreciation from the equation of our model is equated to zero. The values derived for Russia are to be taken with caution given that the first years available cover the end of the Soviet economy, and we have therefore dropped negative values of investment for consistency.

We chose to calibrate the parameter Φ by one tenth of the average share of GDP spent by government on education: the lower the share, the lower the Φ, reflecting the fact that the country does not weigh the future much. The source of the data is the World Bank (World Bank, 2011), where public expenditure on education includes both current and capital spending[15].

In order to estimate the sensitivity of damages to CO_2 levels, *B*, we first need to derive national total damages costs in US$. Although such estimates are the object of wide criticism,

[14] In the countries for which the Penn World Tables report no data for 1960, we consider as the first year the earliest year available that is followed for that country by at least 15 observations.
[15] This includes also government spending on both public and private educational institutions, education administration and subsidies for private entities.

we adopt two different methods for the calibration: first, Nordhaus's DICE model (Nordhaus 2008) with the uniform global damages, independent of the level of capital; and second, Nordhaus' DICE model but with damages dependent on capital, i.e. $\epsilon>0$. We assume that the global mean surface temperature change since pre-Industrial is around 0.85°C in line with recent estimates for the change over the period 1880-2012 (IPCC, 2013).

Using these parameters, we estimate the *DME* for each country, including the first period emissions of all countries in the estimate of *H*. The sensitivity of the *DME* to different values of ϵ is shown in Figure 5. Normalised to the UK's *DME*, Figures 6 and 7 show the results for the two cases of $\epsilon=0$ and $\epsilon=10^{-12}$.

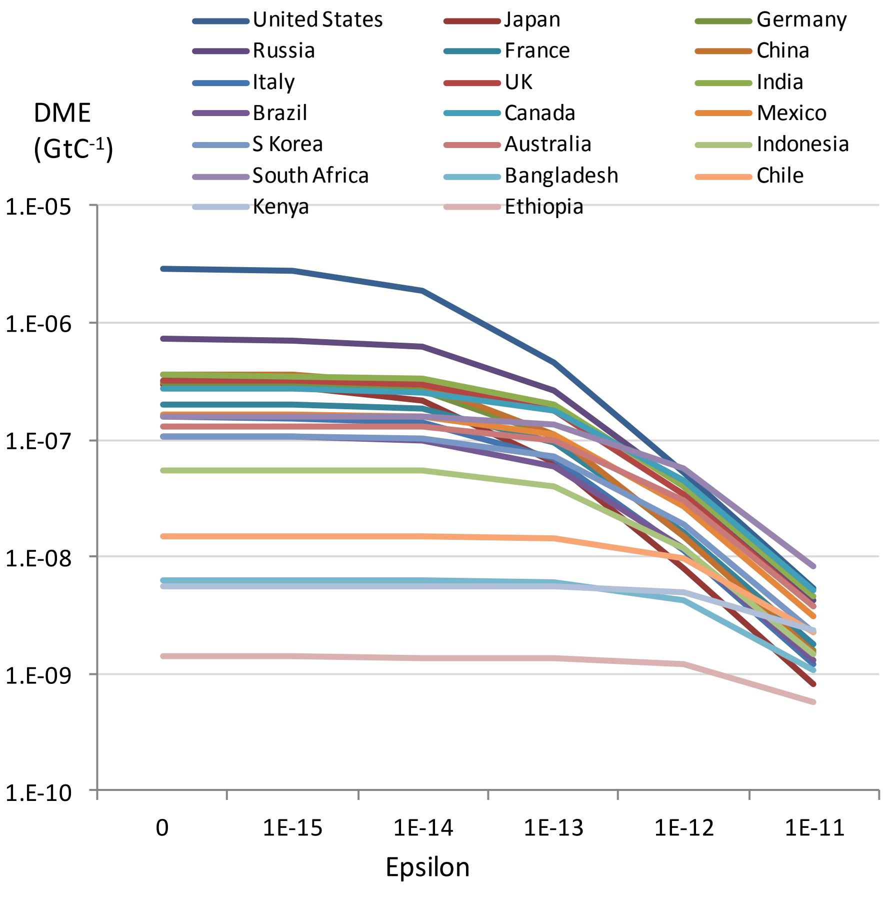

Figure 5: Convergence of DME values as capital sensitivity of damages increases

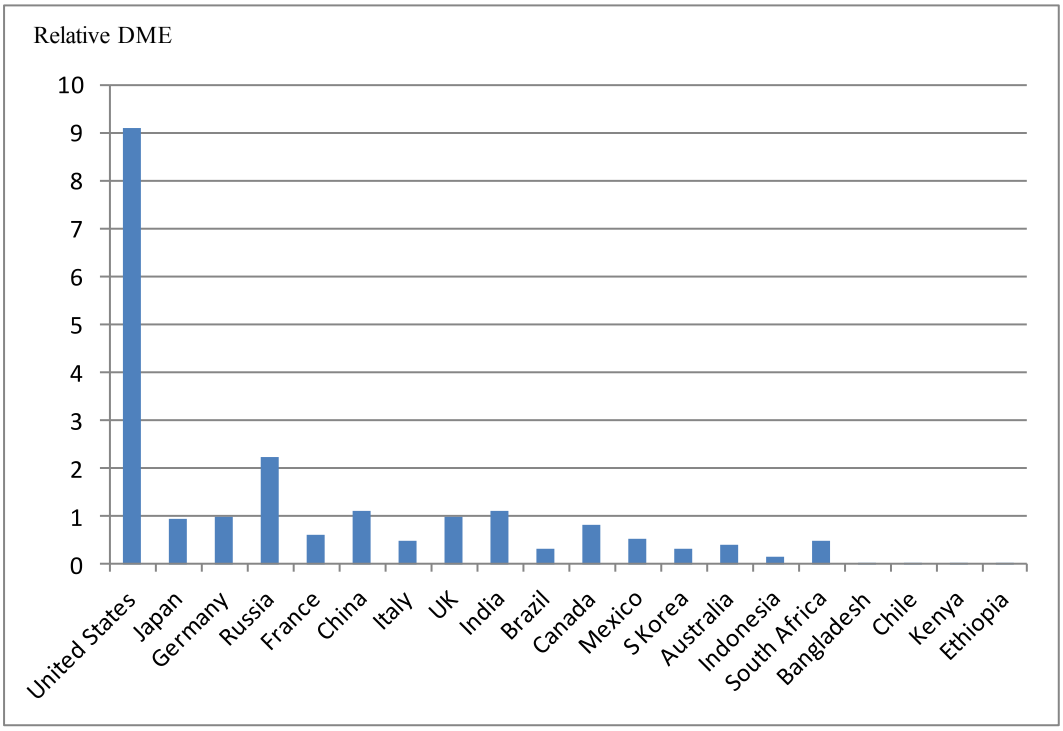

Figure 6. Relative *DME* for ϵ=0 (normalised to UK's *DME*)

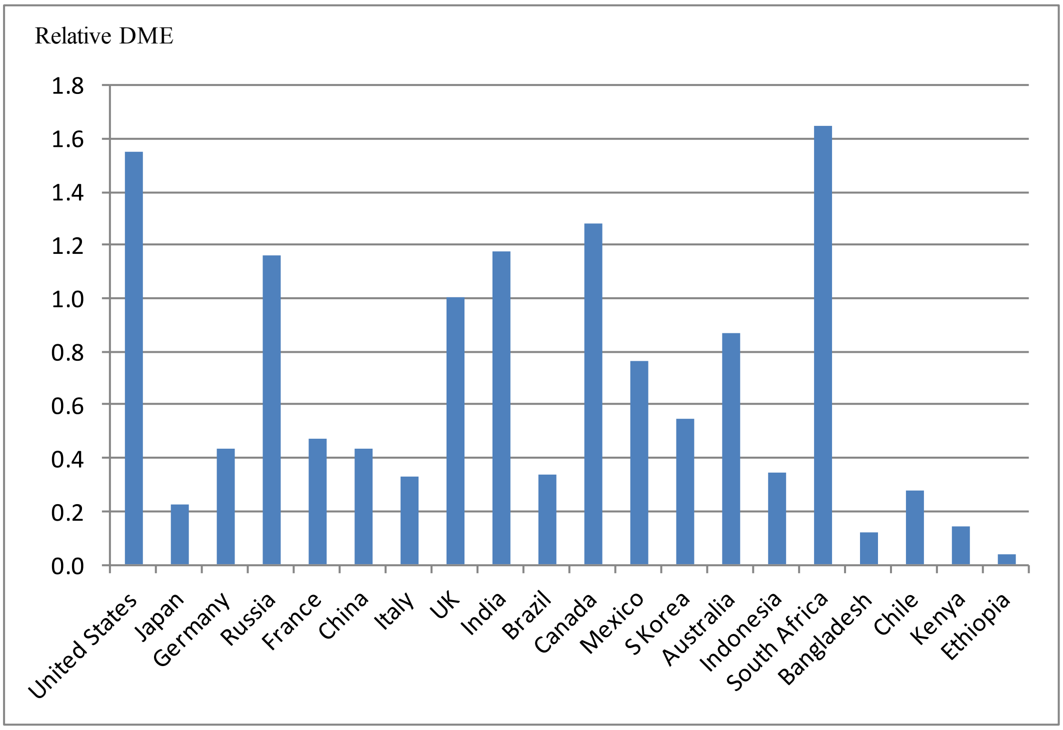

Figure 7. Relative *DME* for $\epsilon=10^{-12}$ (normalised to UK's *DME*)

The importance of regional heterogeneity of damage functions has been explored elsewhere (e.g. Nordhaus, 2010). Here we focus on what effect including capital-sensitive damages might have on *DME*, where Fig. 5 shows dramatic convergence with increasing values of ϵ. For ϵ=0 (Fig. 6), most major economies have a *DME* similar to or stronger than that of the UK; indeed, Russia, China and India all have a higher relative *DME*. As expected, the poorest developing economies all have a very low *DME*. South Korea and Australia have a weaker *DME* than the UK and most other developed economies. However, the US *DME* is almost one order of magnitude greater than that of all of the other major emitters, raising serious questions over the assumption of uniform global damages independent of capital.

For $\epsilon=10^{-12}$ (Fig. 7), the US's *DME* is no longer the largest and is of the same order as that of other major economies. There is also a strong reduction in the relative *DMEs* of some of the other capital-heavy economies (i.e. Japan, Germany, Russia and China), with a smaller reduction in France and Italy. We suggest that China's low *DME* may well be an artefact of their large and relatively unproductive capital biasing down the value of the damages parameter, rather than any robust indication of a weaker propensity to mitigate. Canada, India, Mexico, Australia, South Africa, South Korea, Indonesia, Bangladesh and Chile all see an increase in their relative *DME* when capital-sensitive damages are included. This contrasts with the insensitivity of Brazil's *DME* to this changed assumption. The *DME* of the least developed countries remains far below that of the others, as expected from the stylised political economy of Section 3, with only Italy having a similar *DME* to Brazil and Chile for $\epsilon=10^{-12}$.

6 Conclusion

The stylized model developed in this paper provides an intuitive and tractable framework for conceptualising and analysing the strategic dynamics of the international climate negotiations. By focusing on the trade-off of lifetime consumption against longer-term climate damages and allowing damages to impact on the level, not just the productivity, of capital, the model yields both a political economy of climate negotiations and a methodology for a numerical assessment of individual countries' optimal level of mitigation effort. The political economy is far richer than the simple developed/developing country dichotomy that emerged from the 1992 Framework Convention on Climate Change. In this more complex environment, our proposed new metric (*Desired Mitigation Effort*, or *DME*) may allow the development of quantitative indicators that could provide the basis for an empirically based assessment of the comparability or otherwise of mitigation efforts over time across heterogeneous countries.

Whilst the approach taken in this paper does not include adaptation, technological change or population growth, the convergence amongst the major economies' *DMEs* when damages are assumed to be sensitive to levels of capital is potentially significant for policy. To the extent that this is a concern amongst parties, achieving an intermediate Cournot outcome may be possible in the current round of international negotiations. Many of the major emitting economies have significant economic self-interest in taking effective mitigation action nationally, provided that proportionate action is taken by others. However, the low *DMEs* for China and some smaller but still significant developed economies highlight the importance of achieving a Cournot equilibrium as the outcome of the current phase of negotiations in order to avoid the possibility of a Stackelberg outcome.

References

Allen MR. et al. (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 458:1163-1166.

Barrett S. (2003). Environment and Statecraft. The strategy of environmental treaty-making. Oxford: Oxford University Press.

Barrett S., and Dannenberg A. (2012). Climate negotiations under scientific uncertainty. Proceedings of the National Academy of Sciences, 109(43), 17372-17376.

Boden T.A., Marland G. and Andres R.J. (2010). Global, Regional, and National Fossil-Fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Bonfiglioli A. (2008). Financial integration, productivity and capital accumulation, Journal of International Economics, 76(2), 337-355.

Bossetti V., Carraro C., De Cian E., Duval R., Massetti, E. and Tavoni M. (2009). The incentives to participate in and the stability of international climate coalitions: a game-theoretic approach using the WITCH model (No. 702). OECD Publishing.

Bréchet Th., Gerard F. and Tulkens H. (2011). Efficiency vs. stability in climate coalitions: a conceptual and computational appraisal. The Energy Journal 32(1), 49-76.

Chichilnisky G, (1995). An axiomatic approach to sustainable development. Soc Choice Welfare 13:231-257.

Edenhofer O., Flachsland C., Jakob M., and Lessmann K. (2012). The Atmosphere as a Global Commons–Challenges for International Cooperation and Governance, Discussion Paper 13-58, The Harvard Project on Climate Agreements.

Hall R. and Jones C. (1999). Why do some countries produce so much more output per worker than others? Quarterly Journal of Economics 114, 83–116.

Heston A., Summers R. and Aten B. (2002). Penn World Table Version 6.1, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania.

International Energy Agency (2012). World Energy Outlook 2012.

Intergovernmental Panel on Climate Change Fourth Assessment Report (2007). Climate Change 2007 (AR4) http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm#1.

Intergovernmental Panel on Climate Change (2013). Summary for Policy Makers, Working Group I Fifth Assessment Report.

Leib J. (2013). How Adaptation Changes the Climate Game: Climate Change Regimes in a Non-Cooperative, Asymmetric World, PhD Thesis, Imperial College London.

Keulartz J., Schermmer M., Korthals M. and Swierstra T. (2004). Ethics in Technological Culture: a pragmatic proposal for a pragmatist approach, Science, Technology and Human Values 29(1).

Myhre G., Highwood E.J., Shine K.P. and Stordal F. (1998). New estimates of radiative forcing due to well mixed greenhouse gases, Geophys Res Lett 25:2715-2718.

Nordhaus W.D. (2008). A question of balance: Weighing the options on global warming policies, Yale University Press.

Nordhaus W.D. (2010). Economic aspects of global warming in a post-Copenhagen environment. Proceedings of the National Academy of Sciences 107(26), 11721-11726.

Stern N. (2013). Ethics, Equity and the Economics of Climate Change Paper 2: Economics and Politics No. 84b, Grantham Research Institute on Climate Change and the Environment.

United Nations Environment Programme (2013). The Emissions Gap Report 2013, accessed at http://www.unep.org/pdf/UNEPEmissionsGapReport2013.pdf on 23 January 2014

UNFCCC (2011). http://unfccc.int/files/meetings/durban_nov_2011/decisions/application/pdf/cop17_durbanplatform.pdf accessed on 6 March 2012.

UNFCCC (2013). http://unfccc.int/files/press/releases/application/pdf/20130305_adpclose.pdf accessed on 7 May 2013.

Wigley T.M.L., Richels R. and Edmonds J.A. (1996). Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. Nature 379: 240-243

World Bank (2011). World Development Indicators, Washington.

Appendix 1. One-country solution with disutility of long-term climate damages

We want to maximise a social welfare function that explicitly has an element reflecting utility from discounted consumption over a lifetime and the disutility of climate change on the bequest to future generations. This takes the form:

$$W_{FAR} \equiv U[C_1] + \beta U[C_2] + \Phi\left[U[\mathcal{B}_3] - U[\overline{\mathcal{B}_3}]\right]$$

Where we define the "myopic" bequest as simply the level of capital bequeathed without netting off long term climate damages:

$$\overline{\mathcal{B}_3} \equiv K_2 = (1-\alpha)\{A_1K_1 + (1-d)K_1 - B_2(S_1 - S_n)^2\}$$

Where

$$B_t = B(1 + \epsilon K_{t-1}) \qquad \forall t = 1, 2, 3$$

We can now find the first order conditions (FOCs).

<u>Differentiating wrt K_1</u>

$$\frac{\partial W_{FAR}}{\partial K_1} = U_1'\frac{\partial C_1}{\partial K_1} + \beta U_2'\frac{\partial C_2}{\partial K_1} + \Phi\left[U_3'\frac{\partial \mathcal{B}_3}{\partial K_1} - \overline{U_3'}\frac{\partial \overline{\mathcal{B}_3}}{\partial K_1}\right] = 0$$

This yields after some manipulation:

Equation A1.1:

$$\frac{\alpha}{(1-\alpha)}\beta U_2'\frac{\partial K_2}{\partial K_1} + \Phi\left(U_3' - \overline{U_3'}\right)\frac{\partial K_2}{\partial K_1} - \epsilon\Phi B(S_2 - S_n)^2U_3'\frac{\partial K_2}{\partial K_1} - 2\gamma\Phi B_3(S_2 - S_n)U_3' = U_1'$$

Differentiating wrt alpha, the second FOC is:

$$\frac{\partial W_{FAR}}{\partial \alpha} = -\beta U_2'\frac{\partial K_2}{\partial \alpha} + \Phi\left[U_3' - \overline{U_3'}\right]\frac{\partial K_2}{\partial \alpha} - \epsilon\Phi B(S_2 - S_n)^2U_3'\frac{\partial K_2}{\partial \alpha} = 0$$

Cancelling the common factor yields:

Equation A1.2:

$$\epsilon\Phi B(S_2 - S_n)^2U_3' = \Phi\left(U_3' - \overline{U_3'}\right) - \beta U_2'$$

We can now solve by substituting Equation A1.2 into Equation A1.1 to give:

$$U_1' = \beta U_2'H - 2\gamma\Phi B_3(S_2 - S_n)U_3'$$

Where again

$$\mathrm{H} \equiv [(1-d) + A_1 - \epsilon B(S_1 - S_n)^2]$$

Appendix 2. One country solution with exact form of CO_2 forcing and for linear utility

This appendix provides more details on the specification of Equation For small departures from the neutral level, we can expand the logarithm in terms of x, where

$$x \equiv \frac{(S_{t-1} - S_n)}{S_n}$$

i.e. $\Delta T(t) \approx 5.35\Lambda\left[x - \frac{x^2}{2} + O(x^3)\right]$. We therefore assume that a linear approximation is valid for the range of CO2 levels we are considering, which may be reasonable for CO_2 concentrations up to ~600 ppmv. Further terms of the expansion of the logarithmic term would need to be included at higher CO_2 levels. We here compare the linear approximation with the quadratic and cubic approximations (see Figure A2.1) and also present the exact form solution of the model for the case of linear utility. Figure A2.1 gives the percentage error for the liner, quadratic and cubic approximations to the exact solution of $ln(S_t/S_n)$ for a range of relevant CO_2 concentrations.

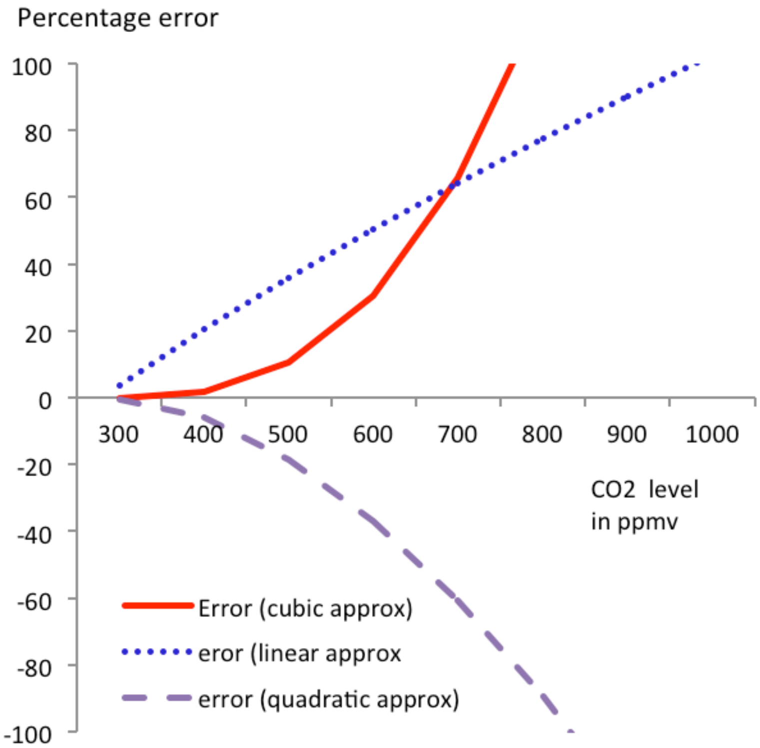

Figure A2.1. Percentage error in the linear, quadratic and cubic approximations to the quantity *ln(St/Sn)* using the Maclaurin series, $\ln(x) \sim x - x^2/2 + x^3/3$.

For linear utility and the logarithmic form of the temperature-CO_2 relationship, the problem is to maximise welfare, W,

$$W_{linear} = C_1 + \beta C_2 - \Phi D_3$$

Where K_2=0 and consumption and damages are given by:

$$C_1 = A_0 K_0 - (K_1 - (1-d)K_0) - B(1+\epsilon K_0)\left[S_n ln\left(\frac{S_0}{S_n}\right)\right]^2$$

$$C_2 = (1-d+A_1)K_1 - B(1+\epsilon K_1)\left[S_n ln\left(\frac{S_1}{S_n}\right)\right]^2$$

$$D_3 = B\left[S_n ln\left(\frac{S_2}{S_n}\right)\right]^2$$

The equation defining the optimal level of S_2 is then:

$$\frac{S_n^2}{S_2} ln\left(\frac{S_2}{S_n}\right) = \frac{\beta\left(1-d+A_1-\epsilon B\left[S_n ln\left(\frac{S_1}{S_n}\right)\right]^2\right)-1}{2\gamma\Phi B}$$

Appendix 3. Data

Table 1. Estimated climate parameters

	Value [a]	Units
S_n	2173.2	Gt CO2
S_0	2838.4	Gt CO2
δ	0.319	-
Conversion factor for 1ppmv to mass of CO_2 [b]		
1ppmv	7.817	Gt CO2 $ppmv^{-1}$

a. Source: IPCC AR5 for 1750 and Mauna Loa record

b. Source: http://cdiac.ornl.gov/pns/faq.html

Table 2. Illustrative parameters for the world economy model

Typical world parameter values		
Neutral level of CO_2, S_n	2173.2	GtCO2
A_{30} world average	0.15	
Phi	Various	
Y world	3.56E+13	$/year
K_0 world	3.02E+14	$
Emissions coefficient, γ_{30}	2.50E-12	GtCO2/$
Annual theta	0.005	
Beta (30 years)	0.86	
S_0 - S_n	874.3	Gt CO2
Carbon cycle delta	0.3186	
Sensitivity to damages, B	200000	$/GtCO2^2
Capital sensitivity of damages	0	
Alpha	0.7	
A_1/A_0	1.3	
S_0	3047.5	GtCO2

Table 3. Economic and emissions parameters for specified countries

Country	A_{30} [a]	Y1990 [b]	Kzero [b]	Total CO_2 emissions (1980-2009) [c]	γ_{30} [a]	Φ [d]
United States	0.145	7.91E+12	5.45E+13	154.30	2.83E-12	0.56
Japan	0.093	3.52E+12	3.76E+13	33.09	8.79E-13	0.39
Germany	0.104	2.08E+12	2.00E+13	27.39	1.37E-12	0.45
Russia	0.111	1.93E+12	1.73E+13	74.83	4.31E-12	0.36
France	0.129	1.48E+12	1.15E+13	11.90	1.03E-12	0.56
China	0.062	1.45E+12	2.34E+13	103.79	4.43E-12	0.22
Italy	0.110	1.42E+12	1.29E+13	12.61	9.80E-13	0.46
UK	0.167	1.41E+12	8.45E+12	16.55	1.96E-12	0.51
India	0.151	1.18E+12	7.81E+12	28.51	3.65E-12	0.35
Brazil	0.133	1.09E+12	8.20E+12	7.95	9.70E-13	0.42
Canada	0.148	7.68E+11	5.19E+12	14.30	2.75E-12	0.55
Mexico	0.140	7.46E+11	5.33E+12	10.65	2.00E-12	0.48
S Korea	0.106	4.90E+11	4.63E+12	9.94	2.15E-12	0.41
Australia	0.127	4.37E+11	3.44E+12	9.13	2.65E-12	0.48
Indonesia	0.114	4.26E+11	3.75E+12	6.78	1.81E-12	0.30
South Africa	0.115	2.07E+11	1.80E+12	10.71	5.94E-12	0.53
Bangladesh	0.183	9.02E+10	4.92E+11	0.71	1.44E-12	0.22
Chile	0.130	7.40E+10	5.71E+11	1.30	2.27E-12	0.38
Kenya	0.192	2.77E+10	1.44E+11	0.22	1.50E-12	0.61
Ethiopia	0.139	2.00E+10	1.43E+11	0.11	7.69E-13	0.38
Sub-total (average for A_{30}, γ_{30} & Φ)	**0.130**	**2.68E+13**	**2.27E+14**	**534.8**	**2.28E-12**	**0.43**
Global value	-	-	-	723.2	-	-
Units	per 30 year period	US$ per year (average over period)	US$	Gt of CO2	Gt of CO2 per US$	none

a. Represents a 30-year period. Multiply by single year value of capital to get 30-year values of output and emissions in that 30-year period.
b. Single year representative value. Source: Heston et al. (2002)
c. Emissions from fossil fuel and cement production. Source: Boden et al. (2010). We are not therefore accounting for emissions from LULUCF.
d. Source: World Bank (2011) World Development Indicators. Φ is the average between 1980 and 2009 of the percentage of GDP spent on public education, when available, divided by 10.

Recent titles

CORE Discussion Papers

2013/44 Volker BRITZ, P. Jean-Jacques HERINGS and Arkadi PREDTETCHINSKI. On the convergence to the Nash bargaining solution for action-dependent bargaining protocols.
2013/45 Pasquale AVELLA, Maurizio BOCCIA and Laurence WOLSEY. Single item reformulations for a vendor managed inventory routing problem: computational experience with benchmark instances.
2013/46 Alejandro LAMAS, Tanja MLINAR, Liang LU and Philippe CHEVALIER. Revenue management for operations with urgent orders.
2013/47 Helmuth CREMER, Firouz GAHVARI and Pierre PESTIEAU. Uncertain altruism and the provision of long term care.
2013/48 Claire DUJARDIN, Vincent LORANT and Isabelle THOMAS. Self-assessed health of elderly people in Brussels: does the built environment matter?
2013/49 Marc FLEURBAEY, Marie-Louise LEROUX, Pierre PESTIEAU and Grégory PONTHIERE. Fair retirement under risky lifetime.
2013/50 Manuel FÖRSTER, Ana MAULEON and Vincent VANNETELBOSCH. Trust and manipulation in social networks.
2013/51 Anthony PAPAVASILIOU, Yi HE and Alva SVOBODA. Self-commitment of combined cycle units under electricity price uncertainty.
2013/52 Ana MAULEON, Elena MOLIS, Vincent VANNETELBOSCH and Wouter VERGOTE. Dominance invariant one-to-one matching problems.
2013/53 Jean GABSZEWICZ and Skerdilajda ZANAJ. (Un)stable vertical collusive agreements.
2013/54 François MANIQUET and Massimo MORELLI. Approval quorums dominate participation quorums.
2013/55 Mélanie LEFÈVRE and Joe THARAKAN. Intermediaries, transport costs and interlinked transactions.
2013/56 Gautier M. KRINGS, Jean-François CARPANTIER and Jean-Charles DELVENNE. Trade integration and the trade imbalances in the European Union: a network perspective.
2013/57 Philip USHCHEV, Igor SLOEV and Jacques-François THISSE. Do we go shopping downtown or in the 'burbs'? Why not both?
2013/58 Mathieu PARENTI. Large and small firms in a global market: David vs. Goliath.
2013/59 Paul BELLEFLAMME and Francis BLOCH. Dynamic protection of innovations through patents and trade secrets.
2013/60 Christian HAEDO and Michel MOUCHART. Specialized agglomerations with areal data: model and detection.
2013/61 Julien MARTIN and Florian MAYNERIS. High-end variety exporters defying distance: micro facts and macroeconomic implications.
2013/62 Luca G. DEIDDA and Dimitri PAOLINI. Wage premia, education race, and supply of educated workers.
2013/63 Laurence A. WOLSEY and Hande YAMAN. Continuous knapsack sets with divisible capacities.
2013/64 Francesco DI COMITE, Jacques-François THISSE and Hylke VANDENBUSSCHE. Verti-zontal differentiation in export markets.
2013/65 Carl GAIGNÉ, Stéphane RIOU and Jacques-François THISSE. How to make the metropolitan area work? Neither big government, nor laissez-faire.
2013/66 Yu. NESTEROV and Vladimir SHIKHMAN. Algorithmic models of market equilibrium.
2013/67 Cristina PARDO-GARCIA and Jose J. SEMPERE-MONERRIS. Equilibrium mergers in a composite good industry with efficiencies.
2013/68 Federica RUSSO, Michel MOUCHART and Guillaume WUNSCH. Confounding and control in a multivariate system. An issue in causal attribution.
2013/69 Marco DI SUMMA. The convex hull of the all-different system with the inclusion property: a simple proof.

Recent titles

CORE Discussion Papers - continued

2013/70 Philippe DE DONDER and Pierre PESTIEAU. Lobbying, family concerns and the lack of political support for estate taxation.
2013/71 Alexander OSHARIN, Jacques-François THISSE, Philip USHCHEV and Valery VERBUS. Monopolistic competition and income dispersion.
2013/72 N. Baris VARDAR. Imperfect resource substitution and optimal transition to clean technologies.
2013/73 Alejandro LAMAS and Philippe CHEVALIER. Jumping the hurdles for collaboration: fairness in operations pooling in the absence of transfer payments.
2013/74 Mehdi MADANI and Mathieu VAN VYVE. A new formulation of the European day-ahead electricity market problem and its algorithmic consequences.
2014/1 Erik SCHOKKAERT and Tom TRUYTS. Preferences for redistribution and social structure.
2014/2 Maarten VAN DIJCK and Tom TRUYTS. The agricultural invasion and the political economy of agricultural trade policy in Belgium, 1875-1900.
2014/3 Ana MAULEON, Nils ROEHL and Vincent VANNETELBOSCH. Constitutions and social networks.
2014/4 Nicolas CARAYOL, Rémy DELILLE and Vincent VANNETELBOSCH. Allocating value among farsighted players in network formation.
2014/5 Yu. NESTEROV and Vladimir SHIKHMAN. Convergent subgradient methods for nonsmooth convex minimization.
2014/6 Yuri YATSENKO, Natali HRITONENKO and Thierry BRECHET. Modeling of enrironmental adaptation versus pollution mitigation.
2014/7 Sanjeeb DASH, Oktay GÜNLÜK and Laurence A. WOLSEY. The continuous knapsack set.
2014/8 Simon BUCKLE, Mirabelle MUÛLS, Joerg LEIB and Thierry BRECHET. Prospects for Paris 2015: do major emitters want the same climate.

Books

V. GINSBURGH and S. WEBER (2011), *How many languages make sense? The economics of linguistic diversity*. Princeton University Press.
I. THOMAS, D. VANNESTE and X. QUERRIAU (2011), *Atlas de Belgique – Tome 4 Habitat*. Academia Press.
W. GAERTNER and E. SCHOKKAERT (2012), *Empirical social choice*. Cambridge University Press.
L. BAUWENS, Ch. HAFNER and S. LAURENT (2012), *Handbook of volatility models and their applications*. Wiley.
J-C. PRAGER and J. THISSE (2012), *Economic geography and the unequal development of regions*. Routledge.
M. FLEURBAEY and F. MANIQUET (2012), *Equality of opportunity: the economics of responsibility*. World Scientific.
J. HINDRIKS (2012), *Gestion publique*. De Boeck.
M. FUJITA and J.F. THISSE (2013), *Economics of agglomeration: cities, industrial location, and globalization.* (2nd edition). Cambridge University Press.
J. HINDRIKS and G.D. MYLES (2013). *Intermediate public economics.* (2nd edition). MIT Press.
J. HINDRIKS, G.D. MYLES and N. HASHIMZADE (2013). *Solutions manual to accompany intermediate public economics.* (2nd edition). MIT Press.

CORE Lecture Series

R. AMIR (2002), Supermodularity and complementarity in economics.
R. WEISMANTEL (2006), Lectures on mixed nonlinear programming.
A. SHAPIRO (2010), Stochastic programming: modeling and theory.